Gamma rays from the Galactic bulge and large extra dimensions

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An intriguing feature of extra dimensions is the possible production of Kaluza–Klein gravitons by nucleon-nucleon bremsstrahlung in the course of core collapse of massive stars. In this event Kaluza–Klein gravitons are copiously produced and a significant fraction of them remains trapped around the newly born neutron stars. They slowly decay into 2 gamma rays, making neutron stars gamma-ray sources. In this letter, we strengthen considerably the limits on the radius of compactification of extra-dimensions for small number n of them, or alternatively the fundamental scale of quantum gravity, considering the gamma-ray emission of the whole population of neutron stars sitting in the Galactic bulge, instead of the closest member of this category. For $n = 1$ the constraint on the compactification radius is $R < 400\mu$m, overlapping with the distance (180μm) at which Newtons law is directly measured. In addition, for n=1 and n=2, the fundamental energy scale of quantum gravity is far beyond the collider technology. These results imply that if $n \lesssim 4$ and if strong gravity is around a TeV, the compactification topology is to be more complex than that of a torus.

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I. INTRODUCTION

Gravitation is exceedingly weaker than the electroweak interaction and, accordingly, the gravity energy scale, or Planck mass, $M_{\text{Pl}} = 1.22 \times 10^{19}$ GeV, is enormously larger than the electroweak scale (≈ 1 TeV). The extreme weakness of gravity relative to other interactions is a deep concern for fundamental physics and calls for an explanation. One elegant way to solve this hierarchy problem is to invoke compactified extra dimensions only allowed to gravity and forbidden to all other forces and particles [1, 2]. Since gravity dilutes in an extra volume, a large number of extra dimensions or a large compactification radius, or both, could lower dramatically the value of the fundamental Planck scale without entering into contradiction with measurements of the gravity law at small scale. Thus, gravity would become strong at energy much lower than the Planck one, possibly as low as 1TeV. In this case, a rich phenomenology is expected at the Large Hadron Collider (LHC) energy, or in high-energy cosmic rays implying, for instance, the production of minuscule black holes with distinctive signatures [3]. This sounds fascinating, but the duty of the physicist is to confirm or disprove this theoretical construction through experiments and/or observations.

In the scenario of Arkani-Hamed, Dimopoulos and Dvali [1, 2] (herein referred as ADD) with n large extra dimensions, gravity propagates in the 4+n dimen-sional bulk of space-time while gauge and matter fields are confined to a four dimensional subspace. It is assumed, for the sake of simplicity, that the n extra dimensions are compactified on a torus whose volume V_n is expressed in terms of a common radius R via $V_n \equiv (2\pi R)^n$. Kaluza Klein (KK) gravitons which propagate in the extra dimensions with momentum p, will appear in our 4–D world as particles of mass $mc = p$. The KK modes are discrete with a density of states R^n. The most intriguing feature of ADD extra dimensions is the possible production of KK gravitons (KKG) by nucleon-nucleon bremsstrahlung in the course of core collapse of massive stars [1, 2, 4]. Furthermore, Hannestad and Raffelt (herein referred as HR) pointed out the existence of a swarm of long lived KKG around neutron stars (NS) [5] . In the core collapse of massive stars reaching a maximum temperature T, KKG of mass $m \approx T$ are copiously produced and a significant fraction of them remains trapped around the newly born NS. They slowly decay into 2γ and e$^+$ e$^-$ pairs, making NS gamma-ray sources.

HR have considered various kinds of astrophysical tests implying high-energy radiation: gamma-ray emission of nearby NS, heating of the surface of NS, extragalactic MeV gamma-ray background due to the combination of all core collapse supernovae in the universe integrated over redshift. As a result, they have set the most severe constraints of all physics on the number n and size R of extra dimensions for small n, at least in the ADD framework, much more stringent than the limits derived by indirect signals of extra dimensions at colliders [6, 7] for $n = 2$ and $n = 3$. For $n \gtrsim 4$, colliders and other constraints become stronger [8]. In the following, we strengthen considerably the limits on the radius of com-

pactification of extra dimensions for small n, or alternatively the fundamental scale of quantum gravity in the ADD scheme, considering the gamma-ray emission of the whole population of NS sitting in the Galactic bulge (GB), instead of the closest member of this category. Following HR, we have taken a fiducial temperature $T = 30$ MeV and density $\rho = 3 \times 10^{14} \,\text{gcm}^{-3}$. For $n < 4$, the mean mass m of core collapse induced KKG is less than 90 MeV [5], and thus their lifetime against the 2γ emission is $\tau_{2\gamma} = 6 \times 10^{9}(100\text{MeV}/m)^3\text{yr}$, sufficiently long to neglect the disappearance of KKG by exponential decay since their production even in the oldest NS of the Galaxy.

II. CONSTRAINTS FROM γ-RAY EMISSION FROM THE GALACTIC BULGE

To set a limit on the high-energy gamma-ray emission from the GB, we use the observations of the diffuse gamma-ray emission from the Galaxy performed by the EGRET instrument aboard the *Compton Gamma-Ray Observatory* [9]. We concentrate in particular on the latitude profile of the observed flux averaged over the $-10° < l < 10°$ longitude interval in the 100-300 MeV energy band. Although the latitude extent of such a diffuse emission is fairly accurately reproduced by a model calculation of the emission based on a dynamical balance between the cosmic rays, magnetic fields, and gravitational attraction of the interstellar matter in the Galaxy [10], the model prediction falls off faster than the observation at $|b| > 3°$. Even if such an excess flux could be attributed to an under prediction of the inverse Compton contribution at these latitudes [9], a fraction of it could eventually due to the GB. Considering that the GB extends over a $6.5°$ radius circle around the Galactic centre, a conservative upper limit $F_{100-300}$ of the GB gamma-ray flux in the 100–300 MeV energy band can then be estimated by summing the whole excess flux which manifests over the $-6.5° < b < 6.5°$ latitude interval. We find $F_{100-300} = 8 \times 10^{-7}$ photons cm^{-2}s^{-1}. Since the KKG decay emission spectrum is such that very few photons of energy > 300MeV are produced, $F_{>100} \approx F_{100-300}$, and we can set to a possible KKG induced gamma-ray flux above 100MeV from the GB an upper limit $F_{>100} = 8 \times 10^{-7}$ photons cm^{-2}s^{-1}.

We aim at comparing the collective gamma-ray emission of the population of NS gathered in the GB to such an upper limit. The GB is a compact stellar system as old as globular clusters, i.e. 13 ± 2.5Gyr [11]. The dominant stellar population of the GB is old with a broad metallicity distribution whose mean value is roughly solar [12, 13, 14]. There is an excess of certain α-nuclei (as Mg) which is a clear signature of dominance of SNII15 (core collapse supernovae which are the producers of NS). From infrared imagery, stellar dynamics and microlensing studies, the total GB stellar mass inferred is $\sim 2 \times 10^{10} M_\odot$ [16]. Motivated by gravitational microlens-

ing studies, the knowledge of the GB has increased dramatically [17]. The stellar mass function in the GB has been determined for low mass stars ($M < 1M_\odot$) still present. Extrapolating to higher masses with a power law mass spectrum with an index $\alpha = -2$, Gould [18] obtains a total number of NS in the GB, $N_{NS} = 10^9$. This index value is consistent with the GB model in Ref. [19], but differs from that adopted in Ref. [20] ($\alpha = -2.3$) which is close to the conventional Salpeter one which applies to the disc of the Galaxy [21]. With $\alpha = -2.3$, the total number of NS in the GB is $N_{NS} = 4.2 \times 10^8$; a steeper index is excluded since it would lead to insufficient iron abundance in GB stars. In what follows, the total number of NS in the GB is taken to be $N_{NS} = (7 \pm 3) \times 10^8$. The integral gamma-ray flux $F(> E_0)$ above the energy E_0 from a single NS at distance d depends on the number n and size R of the extra dimensions through the expression

$$
\begin{aligned}
F(> E_0) \;=\; & 8.1 \times 10^{-23} \,\text{cm}^{-2}\text{s}^{-1} \left(\frac{d}{\text{kpc}}\right)^{-2} \\
& \times \left(\frac{T}{30\,\text{MeV}}\right)^{11/2} \left(\frac{\rho}{3 \times 10^{14}\,\text{gcm}^{-3}}\right) \\
& \times \Omega_n (RT)^n I_n(2E_0/T) ,
\end{aligned} \tag{1}
$$

where Ω_n is the surface of the n-dimensional unit sphere, and $I_n(2E_0/T)$ is an integral tabulated in HR. The total expected gamma-ray flux above 100MeV from the GB is obtained taking d= 8kpc and multiplying by the total number of NS in the GB. Compared to the above derived flux limit $F_{>100} = 8 \times 10^{-7}$ photons cm^{-2}s^{-1}, this yields new upper limits on the compactification volume $V_n = (2\pi R)^n$ of the compact extradimensional torus, or equivalently lower limits on the fundamental scale of the theory, or effective Planck scale $\bar{M}_{4+n}$, as defined by $M_{Pl}^2/(8\pi) = (2\pi R)^n \bar{M}_{4+n}^{2+n}$ in the notation of HR.

Assuming $N_{NS} = 7 \times 10^8$ and T=30 MeV, we obtain the limits presented in Tab. 1, for n ranging from 1 to 7. Compared to a single NS located at 0.12 kpc, with an upper limit on the gamma-ray flux above 100 MeV of 10^{-7} photons cm^{-2}s^{-1} [5], our limit based leads to a substantial gain. The very large number of NS strongly over-compensates the increase in distance and flux limit.

The limits presented in Tab. 1 depend on the total number of neutron stars N_{NS} and on the temperature T. To obtain the limit on R for a generic value of N_{NS}, one should divide the limit in Tab. 1 by a factor $[N_{NS}/(7 \times 10^8)]^{1/n}$. Varying N_{NS} in the interval $3 \times 10^8 < N_{NS} < 10^9$, leads then to a variation of the limit on R of order of $\approx 40\%$ for n=1, and $\approx 10\%$ for n=7. For what concerns the dependence on the temperature, reducing T to 20MeV degrades the limit on R by a factor of about 10, 3, 2, for $n = 1, 2, 3$, respectively. Conversely, increasing T to 50 MeV strengthens the limits by a factor of 16, 4, 2.5.

TABLE I: Upper limits on the compactification radius R (in m) and corresponding lower limits on the fundamental energy scale $\bar{M}_{4+n}$ (in TeV), for $N_{NS} = 7 \times 10^8$ and T=30 MeV. We show for comparison, in parentheses, the limits obtained by Hannestad & Raffelt in Ref. [5], as they would be obtained for a distance to the NS of 0.12 kpc.

n	1	2	3	4	5	6	7
R	3.9×10^{-4}	3.8×10^{-10}	4.2×10^{-12}	4.7×10^{-13}	1.3×10^{-13}	5.4×10^{-14}	2.9×10^{-14}
	(7.7)	(5.3×10^{-8})	(1.1×10^{-10})	(5.5×10^{-12})	(9.2×10^{-13})	(2.8×10^{-13})	(1.2×10^{-13})
$\bar{M}_{4+n}$	7.8×10^4	4.5×10^2	1.9×10^1	2.2	4.7×10^{-1}	1.47×10^{-1}	5.9×10^{-2}
	(2.9×10^3)	(3.8×10^1)	(2.6)	(4.3×10^{-1})	(1.2×10^{-1})	(4.3×10^{-2})	(1.9×10^{-2})

III.   CONCLUSIONS

In conclusion, we considered the production and decay of KKG around NS in the scenario of ADD extra dimensions and discussed the collective gamma-ray emission of the population of NS gathered in the GB. Comparing such emission to the upper limit set by EGRET observations of the Galaxy in the 100 MeV<E< 300 MeV range, we were able to constrain the compactification radius R and the fundamental energy scale $\bar{M}_{4+n}$. We emphasize that for n=1, the compactification radius is $< 4 \times 10^{-4}$m, overlapping with the distance (180μm) at which Newtons law is directly measured [22]. In addition, for $n = 1$ and $n = 2$, the effective Planck scale $\bar{M}_{4+n}$ is far beyond the collider technology. From $n \gtrsim 4$, we recall that the collider and cosmic-ray constraints are more stringent than the astrophysical ones. But for $n < 4$, the improvement is spectacular as far as gamma rays are concerned. It should be noted that comparing the observed luminosity of PSRJ0953+0755 [5] with the one predicted from decaying KK modes leads to a somewhat more stringent constraint than the ones discussed here. However, our new constraints are more reliable since (1) the heating of NS, and even the notion of surface temperature is unclear [23] (2) our new constraints rely on the large statistical weight of a huge collections of objects rather than on just one object. These results imply that if $n \lesssim 4$ and if strong gravity is around a TeV, the compactification topology is to be more complex than that of a torus. Since really the volume of the extra dimensions is constrained, the limits are independent of the relative sizes of different dimensions, except if one or more compactification radii R_i are so small that they cannot be excited at the astrophysical 100 MeV scale, $R_i^{-1} \gtrsim 100$ MeV [24]. In the latter case, however, the problem effectively becomes lower-dimensional where we have seen that the constraints are even stronger. As a curiosity we note that barring these caveats, unification around a TeV requires $n \geq 5$, close to the values $n = 6, 7$ motivated by string theory.

A similar work need to be done in the warped extra dimension model [25].

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